Canadian Conference - Pacific Conference on Earthquake Engineering 2023

Vancouver, British Columbia

June 25th – June 30th, 2023

Risk-Targeted Evaluation of Functional Recovery Performance of Modern Reinforced Concrete Shear Wall Buildings

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ABSTRACT

With growing demand to include functional recovery provisions in future generations of the buildings code, there is a need to (1) formalize methods to evaluate functional recovery performance and (2) benchmark the performance of modern buildings. This study outlines new formulations to perform risk-targeted assessments of functional recovery performance adapted from life-safety methods for collapse performance. The recovery-based performance metrics considered include the 50-year probability of functional recovery time exceeding various time targets and the expected annualized downtime. Building on collapse risk assessment methodologies, disaggregation is used to identify intensity levels that dominate the risk of not achieving functional recovery within various time targets. An illustrative case study of a 12-story modern reinforced concrete shear wall buildings in Seattle, WA is presented to benchmark expected functional recovery performance of current code-conforming buildings. Results of the risk-targeted evaluation show a 40% and a 5% probability in 50 years of functional recovery time exceeding four months and one year respectively. Disaggregation highlights that the risk of exceeding short recovery targets is dominated by frequent earthquakes (i.e., the 100-year) and the risk of exceeding long recovery targets is dominated by larger, rarer earthquakes (i.e., the 975-year). Finally, the expected annual downtime is approximately three days. The risk-targeted performance metrics demonstrate how functional recovery performance can be included in the development of future design provisions. Results of the case study provide valuable insight into the functional recovery performance of modern RCSW buildings that is expected with current design provisions.

Keywords: Functional recovery, Risk-targeted design, Resilience-based design.

INTRODUCTION

Observations from past earthquakes have shown that life-safety performance objectives in modern seismic design standards can result in loss of building function and extensive downtimes after moderate seismic events. These prolonged downtimes have severe economic impacts and often result in permanent population displacement [1–3], most often affecting marginalized communities [4]. Furthermore, recent analytical studies have also estimated prolonged earthquake-induced downtimes in modern buildings. For instance, Molina Hutt et al. [5] reported that the expected downtime for tall modern residential reinforced concrete shear wall (RCSW) buildings was expected to exceed seven months at the 10% in 50-year intensity level and to exceed one year at the 2% in 50-year intensity level. Similarly, Terzic and Kolozvari [6] studied the functional recovery performance of a similar modern RCSW building and estimated the functional recovery time at the design level earthquake to be between eight and 13 months. These extensive downtimes highlight the need for building code provisions to go beyond life-safety to additionally consider recovery time.

The National Institute of Science and Technology (NIST) and the Federal Emergency Management Agency (FEMA) outlined the need to establish new performance objectives for buildings and infrastructure to be expressed in terms of post-earthquake recovery time [7–9]. Functional recovery is defined as the "post-earthquake state in which capacity is sufficiently maintained or restored to support pre-earthquake functionality" [10]. The United States Building Seismic Safety Council (BSSC), by means of the Provisions Update Committee (PUC) has established a Functional Recovery Task Committee intended to develop seismic design provisions for functional recovery performance. Ultimately, the committee intends to integrate such provisions into the 2026 NEHRP Recommended Seismic Provisions for New Buildings and Other Structures. These provisions will inform the development of the 2028 edition of ASCE 7: Minimum Design Loads for Buildings and Other Structures, and ultimately, the 2030 edition of the International Building Code. The work presented in this study provides valuable information in support of this ongoing effort.

Molina Hutt et al. [11], Cook et al. [12], and Terzic et al. [13] recently presented new building-level frameworks to estimate the downtime to reach functional recovery as well as other key recovery states, such as shelter-in-place or reoccupancy. This study uses the downtime estimation framework developed by Molina Hutt et al. [11] and TREADS [14], an open-source, python-based implementation of the calculation methodology. TREADS employs a structure that builds on FEMA P-58 [15] and REDi [16] concepts, to model temporal building recovery trajectories. The framework employs a repair sequencing approach that allows for parallel paths of structural and nonstructural (e.g., exterior, elevator, and staircase) component repair, based on data from past earthquakes [17]. The framework also estimates downtime associated with irreparable and collapse realizations based on observations from the 2010-2011 Canterbury earthquake sequence, by sampling data from Marquis et al. [18] for demolition and financing delays.

The development of downtime estimation frameworks now allows us to evaluate building performance compliance based on recovery time. This paper summarizes work presented in Blowes et al. [19] that outlines methods to evaluate the probability of achieving the functional recovery state within a pre-defined period of time. Analogous to collapse-safety metrics used in today's building codes, we present a risk-targeted assessment of the building functional recovery performance of a modern RCSW building. Calculations are adapted from existing formulations used to evaluate life-safety performance to consider recovery-based performance objectives. The assessment results provide insights into how an RCSW building designed following modern code provisions performs in terms of anticipated recovery time. The first goal of this study is to present a structure that enables the evaluation of building performance in terms of recovery time. The second goal of this study is to benchmark the expected functional recovery performance of modern RCSW buildings. Ultimately, the formulations presented permit the explicit evaluation of building performance and support the development of prescriptive design provisions to achieve functional recovery performance.

INPUT DATA

The archetype building used to evaluate functional recovery performance is a 12-story RCSW building designed by Marafi et al. [20]. The building is situated in Seattle, WA (47.60° N, −122.30° W) and has been used extensively to evaluate collapse risk in the Cascadia region [20,21]. The lateral system was designed to have a 2% drift limit and a flexural demand-to-capacity ratio equal to 1.0 at grade in compliance with minimum ASCE 7-16 [22] code prescriptive requirements. A seismic force reduction factor (R) of 6 was adopted for all buildings, whose design complied with ACI 318-14 [23] requirements for special reinforced concrete shear walls. For more details on the archetype design, readers may refer to Marafi et al. [20].

RISK-TARGETED FUNCTIONAL RECOVERY EVALUATION

Multiple Stripe Analysis

To perform the risk-targeted assessment, the probability of achieving functional recovery by a given time was calculated at five intensity levels. Marafi et al. [20] performed multiple stripe analysis [24] to evaluate the collapse probability of the archetype building at the 100-, 475-, 975-, 2475-, and 4975-year intensity levels. At each intensity level, Marafi et al. [20] selected 100 ground motions that reflected the contribution to the hazard from intraslab, interface, and crustal sources. Damage and loss analyses were then performed in Pelicun [25], an open-source, python-based implementation of the FEMA P-58 methodology [15], using a building performance model developed by Kourehpaz et al. [14]. 2000 Monte Carlo simulations of damage were performed at each intensity level.

In this study, FEMA P-58 damage results were used as an input to TREADS to simulate four parallel recovery paths. The repair paths include (1) structure, interiors, mechanical, electrical, and plumbing, (2) exteriors, (3) elevators, and (4) stairs. In TREADS, repair paths are used to model the progression from the shelter-in-place recovery state until the functional recovery state is achieved (i.e., the building can be used for its basic intended use) [11]. The percentage of the building that is deemed functional at each time step was determined by using the most critical of the four parallel paths. Lognormal distributions of the time required to address different impeding factor delays, such as inspection or mobilization times, were sampled and coupled with the corresponding repair time estimates to develop a governing recovery trajectory for each FEMA P-58 damage realization. Figure 1 provides example recovery trajectories generated using TREADS at the 475-year intensity level, as well as the median and 10th and 90th percentile trajectories.

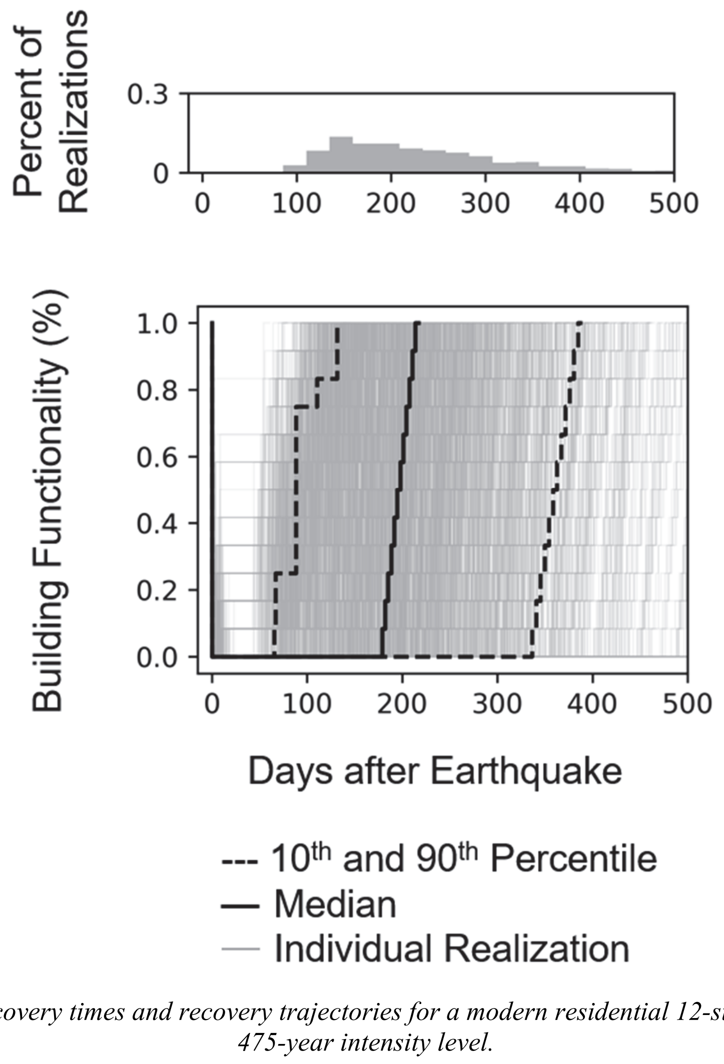

Figure 1: Histogram of recovery times and recovery trajectories for a modern residential 12-story RCSW archetype at the 475-year intensity level.

An empirical cumulative distribution function (CDF) of downtime to functional recovery was developed by leveraging the 2000 Monte Carlo recovery realizations at each intensity level. The functions include both repairable and irreparable realizations. As seen in Figure 2, the median functional recovery time at the 475-year intensity level is 214 days, and at the 2475-year intensity level is 516 days. The empirical CDFs can also be used to determine the probability of achieving functional recovery by a target of target of Y days given an intensity measure, IM, or P(DT_{FR}>Y | IM). For example, the probability of the downtime to functional recovery being less than six months is approximately 35% at the 475-year intensity level.

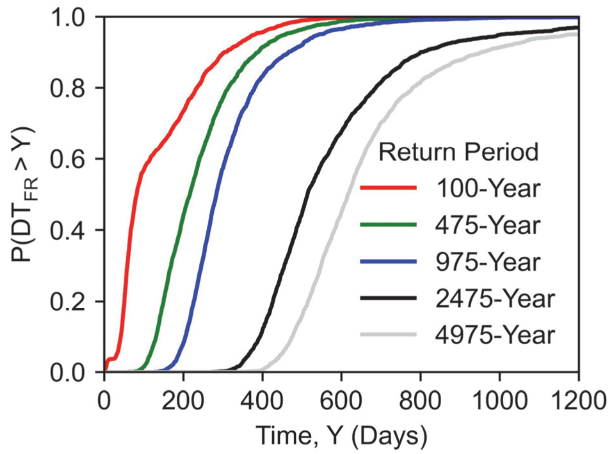

Figure 2: Probability of achieving a downtime to functional recovery of Y days for a 12-story RCSW archetype at range of return periods.

Functional Recovery Time Fragility Fitting

A functional recovery time fragility function provides the probability of exceeding a recovery target conditioned on an intensity measure, IM. At a given time of Y days (i.e., 120 days or 6 months), the probability of not achieving functional recovery by Y days given an intensity measure, or P(DT_{FR} > Y | IM) was calculated from the recovery functions in Figure 2. A lognormal CDF was fit using the maximum likelihood estimation method developed by Baker [26] to the conditional probabilities (i.e., P(DT_{FR}> Y | IM)) as function of the spectral acceleration at the first mode period of the building, $SA(T1)$. A lognormal CDF was used to fit the functional recovery time data because damage, repair times, and impeding factor delays are modeled using lognormal distributions in both FEMA P-58 and TREADS. The downtime to functional recovery fragilities for various time targets are plotted in Figure 3 for the archetype building.

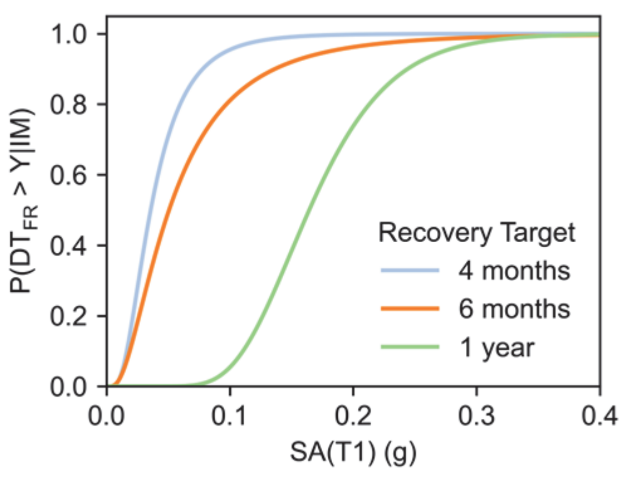

Figure 3: Functional recovery fragility functions for the 12-story RCSW archetype and a range of recovery targets.

Annualized Risk of Exceeding Functional Recovery Targets

Integrating the hazard curve with the downtime fragility enables the calculation of the annualized rate of downtime exceeding Y days, $\lambda_{DT_{FR}>Y}$, as outlined in Equation 1.

$$\lambda_{DT_{FR}>Y} = \int_0^\infty \mathrm{P}(DT_{\mathrm{FR}}>Y \mid IM)\ |d\lambda_{\mathrm{IM}}(IM)| \tag{1}$$

where $\mathrm{P}(DT_{\mathrm{FR}}>Y \mid IM)$ is the downtime fragility and $\lambda_{\mathrm{IM}}(IM)$ is the seismic hazard curve. Using an annualized rate allows for the evaluation of the risk posed by different seismic sources or intensity levels. Much like the standard formulation for collapse risk, disaggregation enables the identification of earthquake intensity levels that drive the risk of not recovering within a threshold time.

50-Year Probability of Downtime Exceedance

Modern design standards, such as ASCE 7-16 [22], currently set target collapse probabilities by considering a 50-year lifespan of a building (i.e., 1% probability of collapse in 50-years). We employ a parallel formulation for the 50-year probability downtime to functional recovery exceeding *Y* days in Equation 2. This procedure provides an understanding of the risk of not achieving functional recovery by a target recovery time over the anticipated lifetime of the building. The probability of not achieving functional recovery by *Y* days in *t* years is calculated from the annualized rate as shown in Equation 2. This formulation assumes that the occurrence of earthquakes over time follows a Poisson process.

$$P_{DT_{FR}>Y}(\text{in } t \text{ years}) = 1 - \exp\left(-\lambda_{DT_{FR}>Y} \cdot t\right) \tag{2}$$

where $P_{DT_{FR}>Y}(\text{in } t \text{ years})$ is the probability over *t* years of not reaching functional recovery within *Y* days and $\lambda_{DT_{FR}>Y}$ is the annual risk of not achieving functional recovery by *Y* days. The 50-year probability of functional recovery time exceeding 4 months, 6 months and 1 year were calculated for the archetype building and the results are summarized in Table 1.

Table 1: 50-Year probability of exceeding target recovery times for modern 12-story RCSW archetype

Target Recovery Time	50-Year Probability of Exceeding Target Time
4 months	40%
6 months	32%
1 year	5%

As is common for evaluating collapse risk, disaggregation is a useful tool for understanding the intensity level that contributes most to the risk, in this case of exceeding a target recovery time. The hazard curve was integrated with the fitted functional recovery time fragility function. Figure 4 shows the normalized disaggregation results for the risk of downtime exceeding four months. Performing the same disaggregation for different time targets shows that 100- to 975-year return periods dominate the risk of exceeding short to moderate downtimes (i.e, one month to one year). The results also show that as the functional recovery target increases, the risk of exceeding the target is governed by larger, more rare earthquakes. It should be noted that the TREADS methodology provides long recovery time estimates even at low earthquake intensities because low thresholds of damage are assumed to impede function and long impeding factor delays are triggered even for low levels of damage. This conservatism is reflected in the disaggregation where the 100-year return period dominates the risk of exceeding both the four- and six-month targets. Further studies should be conducted to test the sensitivity of these assumptions on the disaggregation and to evaluate whether similar results are achieved with alternate downtime estimation frameworks.

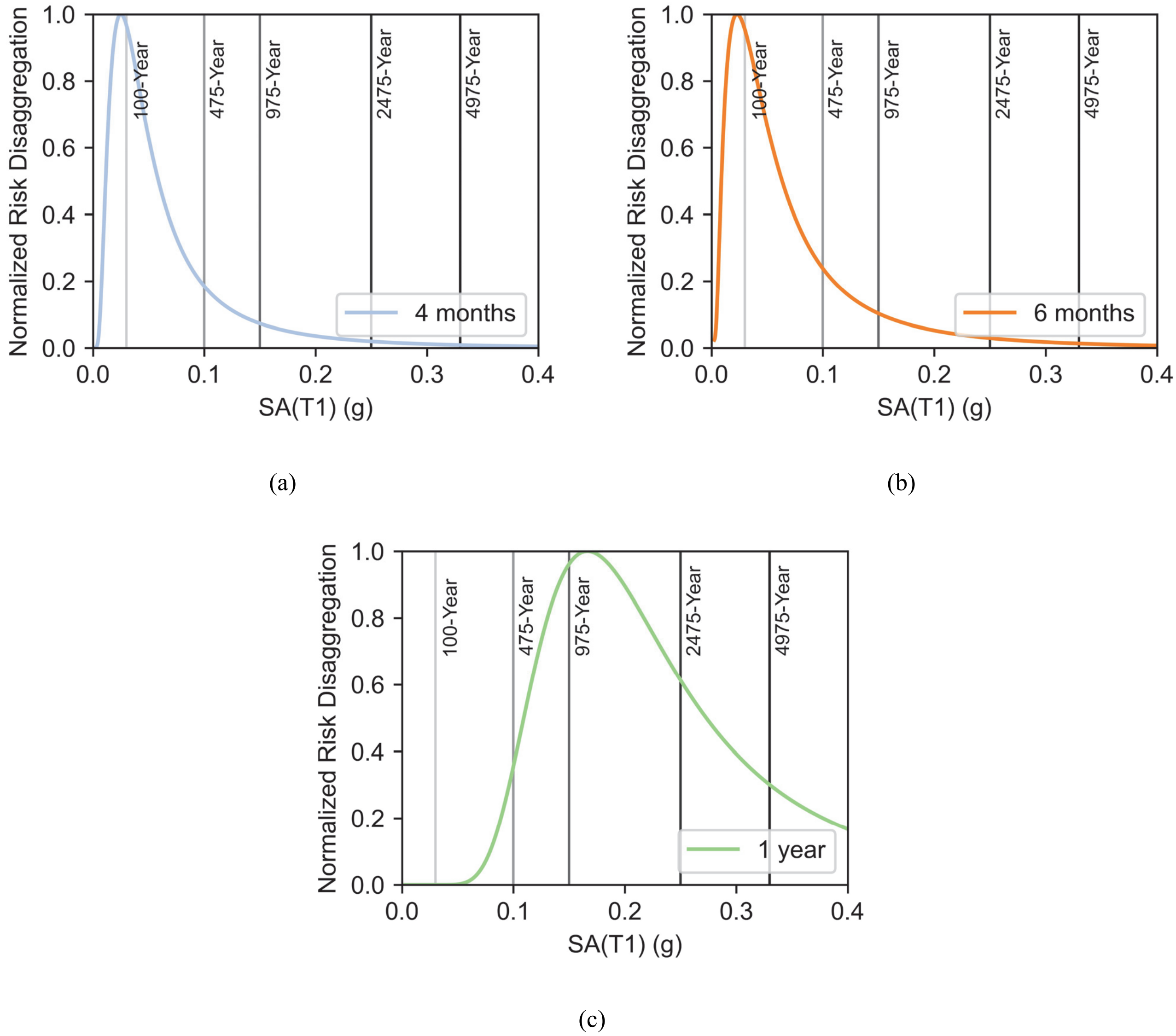

Figure 4: Disaggregation of the risk of the downtime to achieve functional recovery exceeding a) 4 months, b) 6 months, and c) 1 year for a 12-story RCSW archetype.

Expected Annual Downtime

The expected annual downtime to functional recovery, or EAD_{FR}, can also be estimated following a similar formulation to that of the expected annual loss, *EAL*, as illustrated in Equation 3.

$$EAD_{\mathrm{FR}} = \int_{0}^{\infty} \mathrm{E}[DT_{\mathrm{FR}}|IM]|\mathrm{d}\lambda_{\mathrm{IM}}(IM)| \tag{3}$$

where $\mathrm{E}[DT_{\mathrm{FR}}|IM]$ is the expected downtime to functional recovery, DT_{FR}, given an intensity measure, *IM* and $|\mathrm{d}\lambda_{\mathrm{IM}}(IM)|$ represents the annual rate of occurrence of *IM*. The benefit of using the EAD_{FR} to assess functional recovery performance is that functional recovery time fragilities do not have to be developed for different recovery time targets (i.e., *Y* days) and this metric is therefore threshold agnostic. While the EAD_{FR} results are independent of the target functional recovery time, this metric provides no insights of the likelihood of an undesirable outcome, i.e., downtime exceeding a limit beyond which negative societal consequences are expected. The EAD_{FR} for 12-story archetype was calculated using Equation 3 using downtime data for the five discreet hazard levels considered and was found to be 2.8 days.

CONCLUSIONS

This study formalizes methods to perform risk-targeted evaluations of functional recovery performance, with the aim of initiating discussions of how to include functional recovery targets in future design provisions. The formulations presented are adapted from life-safety methods for collapse performance assessment. This study also benchmarks the performance of a modern 12-story RCSW building located in Seattle, WA. The functional recovery time was evaluated using TREADS. Consistent with several other studies, the median downtimes to achieve functional recovery were found to be excessively long, i.e., over 200 days at the 475-year intensity level and over 500 days at the 2475-year intensity level. A risk-targeted analysis was conducted to evaluate the 50-year probability of functional recovery time exceeding 4 months, 6 months and 1 year, resulting in exceedance probabilities of 40%, 32%, and 5%, respectively. A disaggregation of the downtime risk was performed, and it was found that frequent earthquakes dominate the risk of exceeding shorter functional recovery targets (i.e., 4 months and 6 months). As the target was increased, higher intensity levels (i.e., rarer, larger earthquakes) contributed more to the risk of not achieving the recovery time target. Finally, the expected annual downtime was calculated to be approximately 3 days. The results, while informative, were developed for a single archetype building using one downtime estimation framework. Future work should explore the assessment of a wider range of buildings by leveraging all existing downtime estimation frameworks to help establish the baseline functional recovery performance of modern buildings.

ACKNOWLEDGMENTS

This research was funded by Canada's Natural Sciences and Engineering Research Council (NSERC) Discovery Grant No. RGPIN-2019-04599. Kristen Blowes was supported by an NSERC Post-Graduate Scholarship – Doctoral (PGS-D) award. The authors thank Nasser Marafi (Risk Management Solutions) for sharing the structural design and relevant analyses of the case study building used in this manuscript. The authors thank Dustin Cook (National Institute of Standards and Technology) and Francisco Galvis (Thornton Tomassetti, formerly Stanford University) for valuable discussions and insights regarding the findings and methods proposed in this manuscript. Any opinion, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the collaborators or sponsoring agencies.

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